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6. AUTHOR(S)
Steven W. Zucker

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Yale University
P.O. Box 208337
New Haven, CT 06520-8337

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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13. ABSTRACT *(Maximum 200 words)*

(1) With the early stages of edge detection in performance shape, experimental systems to link boundaries of objects in high noise situations became the focus. The mathematical foundations of such systems have been developed based on the curve indicator random field. This random field is being used to develop non-linear filters for grouping whose performance can be maintained in very high noise situations. Such filters involve solving differential equations, and may be implementable directly on the sensor. Initial applications to finding the wake of ships in aerial imagery, and guide wires in surgical applications, suggest how powerful these techniques are. (2) The development of biologically plausible mechanisms to accomplish the tasks of early vision, including edge and curve detection, shading and texture segmentation, and shape matching, are continuing. A serious attempt to understand how such computations could be implemented in the visual areas of primate brains has led us to a significant result in "computational anatomy". This is an activity in which we take our models for connections in curve and texture models and perform the same "experiments" on them that anatomists and physiologists perform on brains. The result is the first coherent set of predictions about the distribution of long-range horizontal interactions in layers 2/3 of ferret, cat,j and primate visual cortices. (3) We have discovered a new flow for deriving the shock-based descriptions that form the heart of our shape-recognition systems. It is based on the Legendre transformation, and gives rise to a dynamical system with biological analogs. Computations appear to be much more stable and easier to implement than the previous level set methods based on curve-evolution theory.

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Final Progress Report on AFOSR F49620-98-1-0424

Steven W. Zucker
Depts. of Computer Science and Electrical Engineering
Yale University
51 Prospect St.
P. O. Box 208285
New Haven, CT 06520-8285
steven.zucker@yale.edu
203-432-6434 (office)
203-432-0593 (fax)

Objectives:

To develop computer vision algorithms based on biological, mathematical, and computational principles that are relevant to automatic target recognition, especially as this pertains to the Air Force.

Status of Effort

This is the final progress report on the above grant. During the tenure of this grant we have solidified the early stages of edge detection, and a computer code remains publicly available for this (see Transitions below). Active interactions with several DoD- and independently-funded industrial organizations have been established.(see Interactions below).

During the course of this grant we focussed our research on two directions, one in early vision and the other in intermediate to high-level vision. On the early vision side we developed curve detection algorithms that function in high-noise situations and are extending our differential-geometry-based algorithms into texture, shading, and stereo. We have started to analyze the interactions between shading and edge structures. These latter projects will be continuing.

In support of our high-level, shape recognition work, systems have been developed to generate generic descriptions of visual shapes, and these are matched to databases using graph matching algorithms. The mathematics are being extended to deal with subgraph homeomorphisms. Both function within a continuous dynamical systems framework, which has important biological analogs as well as implementation advantages.

Accomplishments/New Findings

(1) With the early stages of edge detection in performance shape, experimental systems to link boundaries of objects in high noise situations became the focus. The mathematical foundations of such systems have been developed based on the curve indicator random field. This random field is being used to develop non-linear filters for grouping whose performance can be maintained in very high noise situations. Such filters involve solving differential equations, and may be implementable directly on the sensor. Initial applications to finding the wake of ships in aerial imagery, and guide wires in surgical applications, suggest how powerful these techniques are.

(2) The development of biologically plausible mechanisms to accomplish the tasks of early vision, including edge and curve detection, shading and texture segmentation, and shape matching, are continuing. A serious attempt to understand how such computations could be implemented in the visual areas of primate brains has led us to a significant result in "computational anatomy". This is an activity in which we take our models for connections in curve and texture models and perform the same "experiments" on them that anatomists and physiologists perform on brains. The result is the first coherent set of predictions about the distribution of long-range horizontal interactions in layers 2/3 of ferret, cat, and primate visual cortices.

(3) We have discovered a new flow for deriving the shock-based descriptions that form the heart of our shape-recognition systems. It is based on the Legendre transformation, and gives rise to a dynamical system with biological analogs. Computations appear to be much more stable and easier to implement than the previous level-set methods based on curve-evolution theory. Extensions to 3-dimensional data are very encouraging. The theory has matured to the point where a major paper on this has been accepted to the International Journal of Computer Vision.

Personnel Supported

- Professor Steven W. Zucker
- Mr. Jonas August
- Mr. Patrick Huggins
- Mr. Ohad ben Shahar

Publications

1. Siddiqi, K., Kimia, B., Tannenbaum, A., and Zucker, S.W., On the psychophysics of the shape triangle, *Vision Research*, 2001, **41**(9), 1153 - 1178.

2. Dubuc, B., and Zucker, S.W., Complexity, Confusion, and Perceptual Grouping. Part I: the curve like representation, *Int. J. of Computer Vision*, 2001, **42**(1/2), 55-82; reprinted in *J. Math. Imaging and Vision*, 2001, 15 (1/2), ‘55 - 82.

3. Dubuc, B., and Zucker, S.W., Complexity, Confusion, and Perceptual Grouping. Part II: mapping complexity. *Int. J. of Computer Vision*, 2001, **42**(1/2), 83-115; reprinted in *J. Math. Imaging and Vision*, 2001, 15 (1/2), 83 - 115.

4. K. Siddiqi, S. Bouix, A. R. Tannenbaum and S. W. Zucker, Hamilton-Jacobi Skeletons, *Int. J. of Computer Vision*, to appear, 2002.

5. S. Pizer, K. siddiqi, G. Szekely, M. Damon, and S.W. Zucker, Multiscale medial loci and their properties, *Int. J. of Computer Vision*, 2002, to appear.

6. Chen, H., Huggins, P.S., Belhumeur, P., and Zucker, S.W., Photometric Statistics of Occlusion Edges, *The Learning Workshop*, Snowbird, Utah, April 10-13 2001.

7. M. Pelillo, K. Siddiqi, and S. W. Zucker, Many-to-many matching of attributed trees using association graphs and game dynamics, *Proc. Fourth Int. Workshop on Visual Form*, Capri, May 2001; C. Arcelli, L. Cordella, and G. Sanniti di Baja (eds), *Visual Form 2001*, LNCS 2059, Springer, New York, 583 - 593.

8. P. Huggins and S.W. Zucker, How folds cut a scene, *Proc. Fourth Int. Workshop on Visual Form*, Capri, May 2001. C. Arcelli, L. Cordella, and G. Sanniti di Baja (eds), *visual Form 2001*, LNCS 2059, Springer, New York, 323 - 332.

9. J. August and S.W. Zucker, A field model for contour organization and partial differential equations, *Proc. Third Workshop on Perceptual Organization in Computer Vision* Vancouver, 8 July 2001, 1-1 – 1-4.

10. O. Ben-Shahar and S.W. Zucker, Flowing Toward Coherence: On the geometry of texture and shading flows, *Proc. Third Workshop on Perceptual Organization in Computer Vision* Vancouver, 8 July 2001, 5-1 – 5-4.

11. P.S. Huggins and S.W. Zucker, Folds and Cuts: How shading flows into edges *Proc. Eigth International Conf. on Computer Vision*, vol. II, 153 - 158.

12. J. August and S.W. Zucker, A generative model for image contours: a completely characterized non-Gaussian joint distribution, *Second International Workshop on Statistical and Computational Theories of Vision*, Vancouver, Canada, July 13, 2001.

13. J. August and S.W. Zucker, A Markov process using curvature for filtering curve images, *EMMCVPR 2001, Energy Minimization Methods in Computer Vision and Pattern Recognition*, Sophia Antipolis, France, Sept. 2001; M.A.T. Figueiredo, J. Zerubia, and A.K. Jain (eds.), LNCS 2134, Springer-Verlag, 497 - 512.

14. O. Ben-Shahar and S.W. Zucker, On the Perceptual Organization of Texture and Shading Flows: From a Geometrical Model to Coherence Computation, *Proc. IEEE Conf. on Computer Vision and Pattern Recognition, CVPR01*, Dec, 2001, Kauai, Hawaii.

15. Chen, H., Huggins, P.S., Belhumeur, P., and Zucker, S.W., Finding folds: on the appearance and identification of occlusion *Proc. IEEE Conf. on Computer Vision and Pattern Recognition, CVPR01*, Dec, 2001, Kauai, Hawaii.

16. Huggins, P.S., and Zucker, S.W., Representing edge models vial local principal component analysis, *Proc. European Conf. on Computer Vision*, Copenhagen, May, 2002.

17. Macrini, D., A. Shokoufandeh, S. Dickinson, K. Siddiqi, and S. W. Zucker, View-based 3-D object recognition using shock graphs, *Proc. Int. Conf. on Pattern Recognition*, Quebec City, 2002.

18. Zucker, S.W., Li, G., and Alibhai, S., Geometry of Contour-based Correspondence for Stereo *Proc. 3DPVT*, Padua, June, 2002.

19. Zucker, S.W., Which Computation Runs in Visual Cortical Columns?, in **Problems in Systems Neuroscience**, J. Leo van Hemmen and T. J. Sejnowski (eds.), Oxford University Press, 2001.

20. Zucker, S.W., Relaxation labeling: 25 years and still iterating, in **Foundations of Image Understanding**, L. S. Davis (ed.), Kluwer Academic Publ, Boston, 2001, 289 - 322.

21. Zucker, S.W., Computing in Cortical Columns: Information Processing in Visual Cortex, in **SENSORS AND SENSING IN BIOLOGY AND ENGINEERING**, T. Newcomb and F. Barth (eds.), Springer, in press.

Interactions

- Discussions with Raytheon Corp, Tucson, on SAR/GMTI signal processing using logical/linear operators and neurophysiologically-inspired computer vision.
  Contact: Dr. Harry Schmitt (SCHMITT@WEST.RAYTHEON.COM).
- Participation with FMAH Corp. and Plainsight Systems on Integrated Sensors and Processing using neurophysiologically-inspired computer vision and dimensional analysis.
  Contact: Dr. Ronald Coifman (COIFMAN@FMAH.COM).
- Jonas August completed his Ph. D. thesis, and is now on the staff of the Robitics Institute, Carnegie-Mellon University, Pittsburgh. He is transitioning his curve detection filters to applications in biomedicine and other areas.

Participation at Meetings

- Invited Speaker, *The Mathematical, Computational and Biological Study of Vision*, Mathematisches Forschungsinstitut, Oberwolfach, Germany, November, 2001.
- Invited Speaker, *Alcohol/Neuroscience/Bioinformatics Workshop*, National Institute on Alcohol Abuse and Alcoholism, National Institutes of Health, Bethesda, Sept. 2001.
- Invited Lecturer, *Methods in Computational Neuroscience*, Marine Biological Laboratories, Woods Hole, MA, August, 2001.

Consultative and Advisory Functions

- Editorial Board, Computational Imaging and Vision, Kluwer academic publishers.
- Editorial Board, International Journal of Computer Vision, Kluwer.
- Editorial Board, Journal of Mathematical Imaging and Vision, Kluwer academic publishers.
- Editorial Board, Neural Computation, MIT Press.
- Editorial Board, Neural Networks.
- Associate Editor, Spatial Vision, VNU Science Press.

Transitions

We estimate that more than 2000 copies of our logical/linear system have been requested by anonymous ftp.

See also the *Interactions* listed above.

New Discoveries, inventions, or patent disclosures

None

Honors/Awards

- David and Lucile Packard Professor of Computer Science and Electrical Engineering, Yale University, 1998.
- (By)Fellow, Churchill College, Cambridge.
- Fellow, Canadian Institute for Advanced Research.
- Fellow, Institute of Electrical and Electronic Engineers (IEEE).
- SERC Fellow, Newton Institute for Mathematical Sciences, University of Cambridge.